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EFFECT OF A CHANGE IN DIRECTION ON THE INITIATION OF GAIT

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Abstract

The aim of the current study was to gain further insight on how postural adjustments, prior to Swing heel off, affect the body's center of mass movement during gait initiation. Ten healthy young adults initiated fast and normal gait toward different directions (-15, 0, 15 and 30°) and the center of foot pressure as well as center of body mass velocity were analysed. Results show that the postural adjustments prior to Swing heel off are modified according to the direction and speed of the intended gait. These modifications take into account the physical demands of the task (the Swing limb must be lifted from the ground to take the first step), the parameters of the desired gait (direction and speed of the center of mass) as well as the maintaining of balance during the task.

Acknowledgment

"Science is a slow process". This phrase has been my mantra over the last two years; at times frustrating because I wanted to have the answers right away and at other times reassuring because I obviously did not have them yet.

Understanding how humans work is like piecing together an intricate puzzle. When looking at the picture on the box, the task seems simple enough, but there are an infinite number of pieces. Research on gait initiation has been going on for years and an important part of the puzzle has already been pieced together. However, over the last two years I have been taking those pieces apart examining them, trying to understand why they fit where they do, only to put them back exactly where they came from. To some this may seem as though I have been giving myself a lot of trouble, or "re-inventing the wheel", but to me this has been a necessary step in laying my own foundation of knowledge. Before adding any new pieces, it was necessary to become intimately acquainted with those already in place so that I could fully appreciate this puzzle.

The initial inspiration for the project of this master's degree was the "elevator phenomenon". Imagine a person in front of two elevator doors. A bell signals that the elevator has arrived. The person starts to walk towards one of the doors, only to realise that it is the other elevator which has arrived. The aim was to determine if and how people could reprogram gait initiation when combined with a change in direction when the desired direction was modified. I did not have to study this puzzle very long to realise that it was much more complicated than what could be thought at first glance.

After spending a summer trying out ridiculously complicated (and long) protocols and trying to make footswitches – it was clear that if my intention was to answer this question, if only in part, I would have to keep it simple (K.I.S.S.!). By that time, it was also becoming clear that my goal was to pursue a career in biomechanic research. If I wanted to get off to a good start, I would have to go back to the basics, that is, take apart and examine the pieces of the puzzle already in place. My project thus became the effect of a change in direction on the initiation of gait.

The review of the literature presented in this memoire is a reflection of this stepping back. Over the last two years, I reread my "key" articles every few months, each time understanding them on a completely new level. I was building up my foundation of basic knowledge and this deeper understanding was proof that my efforts were worth the while. It could seem as though I am a slow learner, but I rather think of it as having a lot of inertia – it was hard to get started, but now that I am going... watch out!

I prepared, executed, analysed and wrote-up the study which I am presenting in this memoire with the guidance of Philippe Corbeil, my advisor and co-author of the article "Effect of a Change in Direction on the Postural Adjustments during Gait Initiation". This article has been submitted to the Journal of Biomechanics from which we are presently waiting a response.

Of course, since it is vital to "keep the ball rolling" the protocol used in this study has since been revamped and more participants (young and older adults) have been tested. The results were presented at RQRV's "Les journée scientific" in the fall of 2007 (oral presentation) and at NACOB 2008 (poster presentation) and will be submitted for publication in the near future. In addition, I have prepared a protocol to study reaction times during the different phases of gait initiation (the puzzle pieces are now coming together...). The data was collected (summer 2008) by Julien Rodrigue, with store bought footswitches I might add.

I would like to thank URGUL for their financial support as well as everyone in the lab who helped me learn how to answer tough questions (YES! it is working - thank-you very much!) and adapt to a cold (temperature) working environment. The going has not always been easy, but my experience over the last two years has validated that I am in the right field. My level of motivation you might ask? 10 of course.

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Chapter I – General Introduction

Approximately 4 million years ago [1], our distant ancestors first started to walk on two legs. This transition from quadripism to bipedalism revolutionised how they cared for their young, gathered food and freed their hands to use tools. The change in human stance and gait is considered to be "[...] the fundamental evolutionary adaptation that sets hominids – and therefore humans – apart from other primates" [2].

An obvious effect of bipedalism is that it changed the way humans stand and walk. Compared to the stable quadruped gait, during which three limbs remain in contact with the ground [3], biped gait requires maintaining balance on a single limb for approximately 80% of the gait cycle [4].

An example of the increased difficulty involved in biped stance and gait is the lapse of time between birth and being able to stand up and walk. Before humans can walk without support, 12 to 15 months are required [2] and adult like gait is only reached by the age of 7 or 8 years [3].

Because humans are bipeds, not only has standing and gait been affected, but the transition between these two states, gait initiation, as well. Gait initiation requires the transition from the quasi static equilibrium of quiet stance to the dynamic equilibrium of steady state gait. This transition has been the focus of a number of studies since the late 1970s [5-14]. These studies have demonstrated that gait is initiated by coordinated muscle contractions which modify the forces applied to the ground via the feet and provoke movement of the center of mass (CoM). Gait initiation is associated with a typical Center of Foot Pressure (CoP) displacement, which is modified in a predictable manner in order to produce modified gait [7]. Notably, Breniere et al. found that when the speed of the desired gait is modified the initial posterior displacement of the CoP is adjusted – increased for faster gait and decreased for slower gait [7]. These findings suggest that gait is initiated using precise, pre-planned, postural adjustments [5].

The majority of gait initiation studies have focused on gait initiated straight ahead [5-15], however, in day to day life gait initiation is often combined with a change in direction. Whether it be moving from the stove to the sink while preparing supper, or moving from a shelf to the cart at the grocery store, combining gait initiation with a change in direction is a functional task about which little is known [16].

Studies which have observed single steps taken diagonally [17] have noted changes in the body's Center of Mass (CoM) velocity during the step. The aim of the research presented in this memoire was to examine how the postural adjustments, which provoke gait initiation, are modified in order to combine this action with a change in direction and determine why this resulted in modified CoM velocity.

Chapter II of this document, Review of the Literature, defines and describes gait initiation and goes on to provide an overview of some of the principal research studies which has been conduction on the subject. Chapter III, the article submitted to the Journal of Biomechanics, details the research project which was accomplished over the course of this degree. Finally Chapter IV provides a general conclusion and suggestions for future study of gait initiation.

Chapter II – Review of the Literature

Gait initiation (GI) is the transition between quiet stance and steady state gait. Steady state gait is a state in which gait is maintained at a constant speed toward a constant direction. During Steady State Gait, "the net mechanical work of the body over one stride is zero" [18]. Quiet stance is a quasi static standing posture in which the net moment and net force acting on the body are approximately equal to zero.

Quiet Stance

During quiet stance the center of body mass (CoM) (Fig 1& 2) is located directly above the center of foot pressure (CoP) (Fig 3) which is located mid-way between the feet in front of the ankle joint by approximately 2-9 cm [12]or 24 ± 11% of foot length [9].

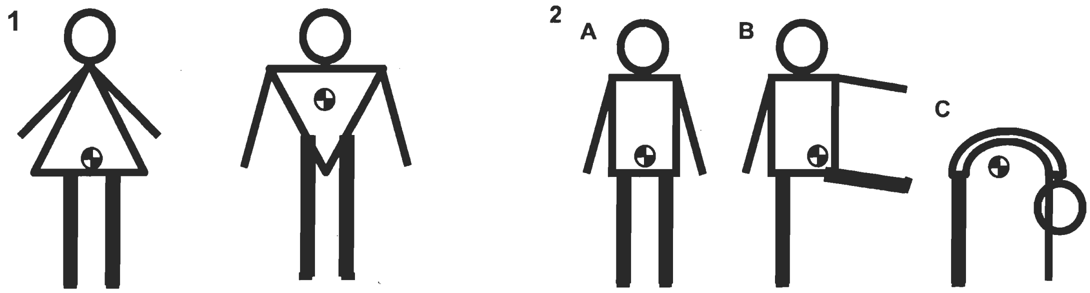

Figure 1 & 2: The center of mass (CoM) also referred to as the Center of Gravity, is the point in space where if concentrated into a single point the mass of the body would be located. Its location depends on the distribution of weight within the body (1) as well as the relative placement of the segments (2). During quiet stance the CoM is typically located in the body close to the navel (2a), however as shown in figure 2b and 2c, the CoM is shifted when body segments are rearranged and can even be located outside of the body [19].

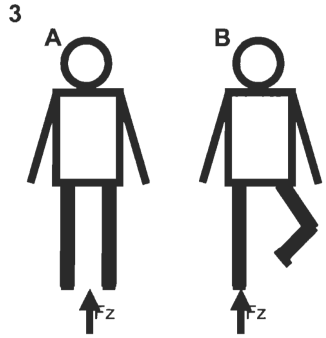

Figure 3: The center of pressure (CoP) is the point of application of the sum of all ground reaction forces which during quiet stance are equal and opposite to the force of gravity applied to the body mass (mg) [4]. The CoP is necessarily within the Base of Support, the area delimited by the body's contact with external surfaces which transmit reactive forces to the body.

In order to maintain this quasi-static standing posture, there is a tonic activation of the Soleus and/or Gastrocnemius (Sol/Gastroc) muscles [9, 12, 13, 15]. This creates a planter-flexion moment around the ankle joint to counter balance the moment created by the CoM which is located anterior to the ankle joint (Fig 4) [12].

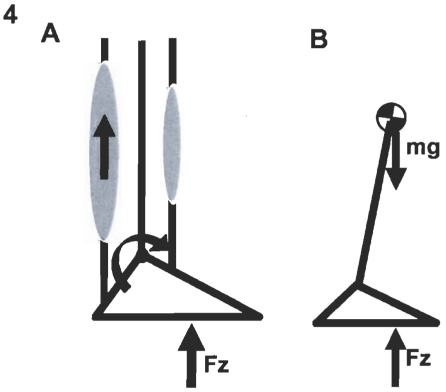

Figure 4: Tonic activity in the Soleus and Gastrocnemius muscles (a) create a planter-flexion moment around the ankle during quiet stance. This keeps the CoP in front of the ankle joint and aligned with the CoM (b) [12].

Although typically referred to as a static posture [11, 13] the CoM is in constant motion during quiet stance [5]. For example, the CoM of a young healthy adult will move within an area of 40mm (lateral sway) by 42 mm (anterior-posterior sway) during 30 seconds of quiet stance on a hard surface with their eyes open and fixing a point straight ahead [20].

The Start of Gait Initiation

Depending on the study, the start of GI has been defined by various events. Some authors consider the start signal to initiate gait, usually a visual cue as the onset of GI [5, 8, 10]. However, the reaction time to this signal tends to be highly variable and depend on factors other than the intended movement, such as concentration and fatigue [8].

Muscle Activation

In order to provoke GI, the body must interact with its environment. This is primarily achieved via muscle activity of the lower limbs [15]. The first activity detected by electromyography (EMG) is an inhibition of the Sol/Gastroc muscles [9, 12, 13, 15]. This is seen in either or both the Swing (leg which will take the first step) and Stance (leg which will start as the supporting leg) limbs [9, 15]. Crenna and Frigo as well as Brunt et al. use the start of Soleus inhibition to detect the start of GI [9, 13].

When Soleus inhibition was isolated via stimulation of the digital nerves of the big toe, it was observed that the CoP drifted backwards slowly [9]. This action alone can only produce a slow forward fall of the CoM [9].

An activation of the Tibialis Anterior (TA) follows the Sol/Gastroc inhibition [9, 12, 13, 15]. Elble et al. use this event to determine the start of GI [12]. This burst of muscle activation occurs approximately 100ms after the onset of Sol/Gastroc inhibition [9] and coincides with the lowest level of Sol/Gastroc activity [12].

The combined inhibition of Sol/Gastroc and activation of the TA creates a dorsi-flexion moment which moves the CoP back [12]. Activation of the TA via direct stimulation of the muscle causes the CoP to shift back at a velocity more than twice as fast as Sol/Gastroc inhibition [9].

The amplitude and duration of the TA burst are influenced by the speed of the initiated gait. The faster the initiated gait, the greater the amplitude ($r = 0.73$) [9] and longer the duration [13] of the TA burst. However, when very slow gait is initiated (39 ± 12% height/sec vs. normal gait 60 ± 10% height/sec), TA activity is absent [9]. In addition, a strong correlation between the amplitude of the TA burst and the backward CoP displacement has been observed ($r = 0.82$ Swing limb, $r = 0.71$ Stance limb) [9].

The initial standing posture also influences TA activity. When gait is initiated from a forward leaning position, the activation of the TA decreases and is absent at the greater amplitudes (in front of the ankle joint by 59 ± 12% of foot length for the Swing and 56 ± 11% for the Stance limb) [9]. The latency between Sol/Gastroc inhibition and TA activation is modified by gait speed. The delay between the two events is decreased at the faster speeds (r = 0.85) [9].

Movement of the Center of foot Pressure

Approximately 100 to 200 ms after the onset of Sol/Gastroc inhibition, the dorsi-flexion moment created around the ankle joint causes the CoP to shift backwards [9]. The magnitude of the posterior displacement of the CoP is associated with the speed of the intended gait. The backward shift is reduced when slow gait is initiated and increased when fast gait is initiated [7]. In fact, Breniere et al. suggest that the forward velocity which can be achieved by the end of the first step during GI is limited by the length of the base of support, in other words, how far back the CoP can shift [7]. Polcyn et al. observed that the time integral of the posterior CoP displacement is highly correlated with the generated forward momentum (r = 0.96 ± 0.01) as well as with the speed of gait (r = 0.88 ± 0.07) [14]. In addition, the intercept of the regression line between the generated momentum and the time integral of CoP displacement is close to zero. This indicates that the posterior CoP shift is the principal factor which generates forward momentum during GI [13]. The maximum posterior displacement of the CoP coincides with the peak of the TA burst [9].

Postural Adjustments

The sequence of events (EMG activity and CoP shift) which occur prior to the onset of movement has been referred to as Anticipatory Postural Adjustments (APA) [21, 22]. However, APA are defined as actions which precede the onset of a perturbation in order to minimise its destabilising effect [9, 23]. During GI, the goal is to transition the body from a static, balanced position to a controlled forward fall. The events which occur prior to GI are produced in order to provoke the movement rather than reduce the effects of postural perturbations [7]. The events at the start of GI, prior to the onset of movement, will therefore be referred to as Postural Adjustments (PA) for the remainder of this document.

Movement of the Center of Mass

Movement of the CoM begins approximately 290 ms after activation of the TA [12]. Contrary to what was stated by Mann et al. [5], the CoM does not shift posteriorly at the start of GI, but rather forward through out the entire transition [12, 15].

This misinterpretation of the consequences of the CoP shift can be attributed to the authors' definition of the link between the CoP and CoM; "The center of pressure, which represents the projection of the center of mass of the body [...]" [5]. This definition is applicable during quasi-static quiet stance, but not during the dynamic initiation of gait [15]. Rather, during GI there is a decoupling of the CoM and CoP. The posterior shift of the CoP toward the Swing limb causes a forward acceleration of the CoM toward the Stance limb [13]. It is the detection of CoM acceleration which is used by Breniere and his collaborators to determine the start of GI [6, 7].

The movement of the CoM during GI has been observed using kinematics and force plate data. Certain authors have used video analysis to track the movement of the body during GI [8-10, 12, 13] where as others have calculated the velocity and position of the CoM with the forces recorded using force plates [6, 7, 11, 15].

Measuring Center of Mass Displacement Using Kinematics

The Kinematic method of measuring CoM displacement is based on the distribution of mass within the body as well as the relative placement of the segments (Fig 1 & 2). Video analysis is used to locate each body segment. A model which provides estimated values of individual segment mass and CoM location within the segment is then applied to the data. A weighted average of the position of the CoM of each segment is used to estimate the position of the total body CoM.

This method is typically considered to be the most reliable method of measuring the CoM [24]. It has been used to test the validity of other methods of measuring the CoM [25]. However, the Kinematic method of measuring CoM is "sensitive to errors in the anthropometric model" [24]. Also, depending on the equipment used, the Kinematic method can be a costly and/or time consuming measurement.

Measuring Center of Mass Displacement Using Ground Reaction Forces

The ground reaction forces obtained using forces plates provide measurements of the vertical reaction force (subject's mass x gravity) as well as medial lateral and anterior posterior shear forces. When divided by the subject's mass these readings provide information on the CoM acceleration in each of these directions. Integrated once, velocity values are obtained and a second time position values. However, in order to be accurate, it is necessary to use adequate integration constants (initial values of velocity and position) when performing these calculations.

In their early studies, Breniere et al. assumed that the initial values of acceleration and velocity were equal to zero and that the initial horizontal position of the CoM was the same as that of the CoP [6, 7, 11]. However quiet stance is quasi-static, the CoM does move within a small area during this time [5, 20].

An improvement of this method was proposed by Shimba who suggested using a least squares curve fitting to determine approximate initial velocity and position values [26]. This technique has been shown to be a robust method for a number of postural tasks [24].

Yet another method of determining the initial CoM velocity and position values was proposed by Zatsiorsky and King, the Zero-point-to-zero-point Integration method. This method utilises the property that when the CoM is aligned with the CoP in the medial lateral or anterior posterior axis, the corresponding value of shear force is equal to zero. Since the position of the CoP is known, the CoM position at these events is also known [27].

In order to apply the zero-point method, the CoM acceleration is integrated twice between two zero points, a first time using an initial velocity of zero and the correct initial position. The calculated end position is then subtracted from the measured end position and the difference is divided by the time interval of the integration. The result of this is the correct initial velocity. The double integration is then recalculated using the correct velocity and position constants. Since zero values are rare when sampling data digitally, Zatsiorsky and King suggest using points of zero-crossing as initial and final points for the integration [27].

It has been demonstrated that this method provides CoM trajectories similar to those obtained using the Kinematic method [25]. In addition, Lenzi et al. demonstrated that the zero-point method was better than the Kinematic method when estimates of body segment parameters lacked precision [24].

Another method of measuring CoM movement using ground reaction forces is the Low-Pass Filter method (LPF) developed by Breniere and his colleagues. This method uses the horizontal CoP position to calculate the horizontal CoM position. This is achieved by passing CoP data through a low-pass filter. The parameters of this filter are determined using the Natural Body Frequency, which is calculated using anthropometrical data (body mass, height of the CoM and Inertia of the body with respect to the CoM) as well as the value of gravity [28].

Lafond et al. compared the LPF method to the Kinematic method and found that it was more effective for movements of larger amplitude (oscillations verse quiet stance). However, even in these trials, the LPF method underestimated the CoM displacement [25].

End of Gait Initiation

Once the CoP has reached is maximum posterior displacement and the forward fall of the CoM has been initiated with sufficient torque to achieve the desired velocity of gait (greater velocity requires greater torque), the heel of the Swing limb is lifted from the ground and the first step of gait is taken [7]. The definition of when the GI is complete and steady state gait is achieved varies between studies.

Authors such as Mann et al. and Breniere et al. have defined GI to be over once the velocity of CoM progression has reached that of steady state gait. However Mann et al. observed at this required three steps [5], whereas Breniere et al. discerned that the desired progression velocity was reached by the end of the first step [6]. This discrepancy can be attributed to the authors' definition of having reached progression velocity. Mann et al. measured the average pelvic travel [5] whereas Breniere et al. measured the peak CoM velocity at the end of the first step [6]. In fact Breniere et al. noted that differences between peak velocity and average progression velocity increase when gait velocity is increased [6].

Other studies have defined the end of GI as toe-off of the Stance limb [8, 10, 12, 13] or heel strike of the Stance limb [5]. In certain studies choice of the end of GI was made due to the constraints of the equipment; the range of the motion capture system [8] or the size and layout of the force plate(s) [13].

Invariant Components of Gait Initiation

A common theme in the study of GI is the invariance of its components. Among the invariant components observed are the synergies between Sol/Gastroc inhibition and TA activation [9, 13], the stereotypic displacement of the CoP [12, 13] and the frequency of the first step [6, 7]. These findings have lead some authors to describe GI as the result of a motor program [9, 10, 13] and others to describe GI as governed by the body's physical characteristics [6, 7, 11].

Motor Program

A motor program is "[a] structured set of central commands that define a temporal relationship of muscle activation to satisfy a goal oriented task" [13]. It is produced in a feed-forward manner such that the movement is executed without any peripheral feed back [13].

Findings which support the notion that GI is provoked using a motor program include correlations between Sol/Gastroc inhibition and TA activation [13]. The amplitude and timing of which can be scaled up or down depending on the velocity of the desired gait and the body's posture prior to GI. When the speed of the initiated gait is increased, the interval between the inhibition of the Sol/Gastroc and the activation of the TA is shortened ($r = 0.85$) [9]. When the forward lean of the initial standing posture is increased, the time delay between Sol/Gastroc inhibition and TA activation decreases and eventually becomes negative (TA activated before Sol/Gastroc inhibition) [9].

This motor program (Sol/Gastroc inhibition followed by TA activation) has also been associated with other forward oriented actions such as fast forward bends of the head and trunk, standing up from a sitting position and rising on the tips of the toes [9].

Later studies have suggested that GI is actually a combination of two motor programs. The first program governs the transition from the onset to heel-off of the Stance limb. The duration of this first program remained constant between two speed conditions and three tasks (GI, stepping, stepping over a 10cm obstacle). The second program is attributed to the rapid increase in forward velocity of the CoM [13]. This concept is supported by the observation noted by Breniere et al. that frequency of the first step is fixed and that the fine tuning of gait, such as increasing progression velocity is achieved after the first step [11].

Inverted Pendulum

The inverted pendulum is a simplified, single joint – one degree of freedom, model of the human body often used to analyse standing posture and gait [11, 29, 30]. The typical Inverted Pendulum Model includes the CoM rigidly linked to the ankle joint (point of pivot) by a segment equal to the distance between the CoM and the ankle during quiet stance. Some Inverted Pendulum Models also include a foot, which allows the point of force application (CoP) to be located elsewhere than the ankle joint [29].

Breniere et al. proposed that during GI, the body acts as an inverted pendulum and therefore the frequency of the first step is a function of the body's mass and moment of inertia as well as the height of the CoM from the ground [6, 11]. These constants can be used to calculate the half period of the pendulum, the frequency of which agrees with the measured first step frequencies (Equation 1) [11].

$$T/2 = \sqrt{\frac{J_G + ml^2}{mgl}}$$

T : Period of the pendulum
J_G : Moment of inertia of the body
m : Mass of the body
g : Gravity
l : Height of the CoM

Equation 1: equation to calculate the half period of the inverted pendulum model [11]

This notion is supported by the time to reach peak velocity at the end of the first step, which is independent of the speed of the initiated gait. When speed is increased, the anticipation phase (first measured acceleration of the CoM to Swing heel-off) is increased ($r = 0.73$) and the execution phase (Swing heel-off to peak velocity of the CoM at the end of the first step) is decreased ($r = -0.80$), however the combined time of both this phases remains unchanged [7]. Further proof was provided by an experiment in which step length was controlled. For the short (0.5m), normal (0.7m) and long steps (0.9m) the step frequency remained unchanged (approximately $1.6s^{-1}$, $p>0.10$) and the velocity (step length x step frequency) was increased ($p<0.001$) [11].

Medial Lateral Components of Gait Initiation

To date, the main focus of GI studies has been movement in the anterior posterior direction [9], [10]. However, because humans are bipeds, maintaining balance during single support must also be considered during GI [11-13].

During quiet stance, the horizontal position of the CoP and CoM is midway between the legs

[5]. Before the first step of GI, the Swing limb is unloaded [7]. This is achieved by first increasing the vertical force under the Swing limb (reaching 85% of body weight) [8] which causes the CoP to shift toward the Swing limb at the same time as it shifts backwards [12]. This action has been attributed to the shortening of the Stance limb achieved by 3 to 9° of flexion in the hip and knee [8, 12]. The result of this initial loading of the Swing limb is the acceleration of the CoM toward the Stance limb and ultimately the unloading of the Swing limb [13].

When gait is initiated straight ahead, the medial lateral components of GI are perpendicular to the desired direction of gait and do not directly contribute to the forward progression of the CoM. There is no correlation between lateral CoP shift and the speed of gait, which indicates that the demands for medial lateral momentum remain unchanged throughout various gait speeds [13]. However, movement in this plane assures that balance is maintained during single stance [17].

When a limb is lifted (the Swing limb) from a quiet stance posture, the CoP necessarily shifts under the limb which is still in contact with the ground (the Stance limb). If the CoM is not displaced prior to this action, the sums of the moments and of the forces of the system are no longer equal to zero and the CoM falls toward the side of the Swing limb. As this happens, the CoM moves further away from the CoP and both the moment and lateral reaction forces increase, a fall will occur unless a recovery step is taken [17].

In order to maintain balance during single support stance, the CoM must be moved toward the Stance limb so that it comes to a rest above this limb before or as the Swing limb is lifted. However, during gait initiation, static equilibrium above the Stance limb is not desired, but rather a delay in the fall of the CoM toward the Swing limb until the first step can be taken. To achieve this, the CoM is accelerated toward the Stance limb prior to Swing heel-off [17].

During GI, when the Swing limb is lifted from the ground and the CoP is shifted underneath the Stance limb, the CoM is accelerated toward the Swing limb. The amplitude of the initial acceleration toward the Stance limb is such that the CoM velocity reaches zero and the CoM stops moving toward the Stance limb before having reached the border of the new base of support (the Stance foot). At this point the CoM falls toward the side of the Swing limb. A similar pattern of lateral CoM displacement continues during steady state gait [17].

The majority of GI studies focus on gait initiated straight ahead [5-15], however day to day life is filled with turns and changes in direction [16]. Lyon and Day found that the CoM velocity and displacement toward the Stance limb at toe-off of the Swing limb were reduced when a step was taken diagonally toward the Swing limb rather than straight ahead. The result of this was that the CoM stopped moving toward the Stance limb further from the new base of support (the Stance foot) and the fall of the CoM toward the side of the Swing limb was increased [17].

The modifications of the postural adjustment which initiate gait toward different directions (both toward the Swing and Stance limbs) and provoke the differences in CoM velocity have not yet been observed. Information about these modulations will provide insight on how the body manages the various physical constraints of GI (example single support) while achieving the desired goal (gait initiated with a change in direction). The effects of a change of direction on the postural adjustments during gait initiation, is the focus of the study presented in the following chapter.

Chapter III – Article

Abstract

The initiation of gait (GI) from quiet stance is preceded by postural adjustments which accelerate the body's center of mass (CoM) forward and unload the Swing limb in order to take the first step. Studies of GI have primarily focused on gait initiated straight ahead, however, in everyday life GI is often combined with a change in direction. Ten young adults initiated gait with their right limb toward four directions (to the left: -15°; straight ahead: 0°; to the right: 15 and 30°) at two gait speeds (fast and normal). Compared to straight ahead GI, when gait was initiated toward the positive directions the initial lateral and posterior displacements of center of foot pressure (CoP) were reduced ($Ps<0.001$). When gait was initiated toward the negative direction, only the lateral CoP displacement was increased when compared to straight ahead GI ($P<0.001$). At the first step of the Swing limb, the velocity of the CoM in the desired direction remained slower for the 30° condition ($P<0.001$) whereas no difference was found between directions for perpendicular CoM velocity. These results suggest that both the lateral and posterior components of the postural adjustments are modulated in order to initiate gait toward a predetermined direction. By the first step, the orientation of CoM displacement is toward the desired direction of gait, however additional adjustment may be required to reach the desired forward velocity when gait is initiated in combination with a large change in direction.

Introduction

Gait initiation (GI) is the transition from quiet stance to steady state gait. Mann et al. (1979) were among the first to observe the characteristic trajectory of the net center of foot pressure (CoP) during this action. During quiet stance the CoP is located between the feet slightly anterior to the malleolus (Mann, Hagy et al., 1979; Breniere, Do et al., 1981; Crenna and Frigo, 1991). When gait is initiated, the CoP initially shifts posteriorly toward the foot which will take the first step (Swing limb). The CoP then shifts toward the other foot (Stance limb) and finally shifts forward under the Stance limb. Breniere et al. (1981) demonstrated that this CoP trajectory was associated with the forward fall of the body's center of mass (CoM) toward the Stance limb. The posterior shift of the CoP accelerates the CoM forward and the lateral shift toward the Swing limb accelerates the CoM toward the Stance limb. Strong correlations (rs>0.85) were observed between the time integral of the posterior CoP shift and the forward momentum of the CoM as well as between the lateral CoP shift toward the Swing limb and the CoM momentum toward the Stance limb (Polcyn, Lipsitz et al., 1998). These postural adjustments (PA), which occur prior to Swing heel-off, unload the Swing limb for the first step and commence the forward progression of the CoM (Breniere, Do et al., 1987).

Further studies have shown that the PA are modulated with regards to the determinants of the intended gait. For instance, an increase in the speed of the initiated gait is associated with an increase in the posterior shift of the CoP prior to Swing heel-off. Within the limits of the base of support (i.e. foot length), the desired speed of gait can be achieved by the end of the first step by modulating the posterior shift of the CoP prior to Swing heel-off (Breniere, Do et al., 1987).

Previous studies have primarily observed GI when the desired direction of gait is straight ahead (Mann, Hagy et al., 1979; Breniere, Do et al., 1981; Crenna and Frigo, 1991), in which case the lateral component of CoM movement is perpendicular to the desired direction of gait and does not directly contribute to forward progression. However, in everyday life, GI is often combined with a change in direction (Glaister, Bernatz et al., 2007). Lyon and Day (1997) observed that, compared to a step taken straight ahead, when a step was taken diagonal toward the side of the Swing limb, the CoM velocity as well as CoM displacement toward the Stance limb were reduced at toe-off of the Swing limb. The reduction of these components, required to maintain balance during single support, lead to the CoM falling further toward the Swing limb, the desired direction of the step. The aim of this study was to determine how the PA are modulated in function with the desired direction of gait and to determine the effect of the PA on the CoM velocity at the start and end of GI.

When GI is combined with a change in direction, two strategies for taking the first step are possible. The Swing limb can either be on the same or on the opposite side of the desired direction of gait. This study considers that with the former strategy, gait is initiated toward a positive direction and with the latter strategy, toward a negative direction. When gait is initiated toward a negative direction, the Swing and Stance limbs cross during the first step. This study observed the effect of initiating gait toward positive and negative directions.

Taking into consideration that the initial posterior shift of the CoP toward the Swing limb causes the CoM to fall forward toward the Stance limb (Breniere, Do et al., 1981), it was expected that when gait was initiated toward a positive direction, a smaller lateral CoP shift would provoke a slower CoM velocity (Lyon and Day, 1997). However when gait was initiated toward a negative direction it was hypothesised that the lateral CoP shift would be increased and provoke a greater CoM velocity toward the Stance limb, in order to aide the progression of the body toward the desired direction. In addition, it was expected that the CoM velocity at the start of GI would be different depending on the desired direction of gait, but that by heel strike of the first step, all differences would be eliminated.

Methods

Participants and apparatus

Ten healthy adults (5 men, 5 women; age 22.6±2.6years; height 1.70±0.09m; weight 62.7±9.3kg; BMI 21.7±2.9kg/m2) participated in this study after giving their written consent. Prior to recruitment, this study was approved by the Université Laval ethics committee. Participants initiated gait from an AMTI (OR6-5-1) force platform embedded into a walkway. Ground reaction forces (GRF) and moments were amplified prior to being sampled at 1000Hz (12bit A/D conversion). Data for kinematics, electromyography and foot switch analysis were also recorded, but only the force platform data were analysed in the present study. Prior to analysis, data were filtered using a dual pass 3rd order Butterworth filter with a 10Hz low-pass cut-off. Participants wore a harness during the experiment.

Experimental protocol

At an auditory start signal, participants initiated gait and walked the length of the 4m walkway. In order to assure that gait would be initiated toward both positive and negative directions, participants always initiated gait with their right limb. Gait was initiated from -15° (negative direction), 0° (control, straight ahead gait), 15° and 30° (positive direction) starting angles. The change in direction was achieved by rotating the starting position of the participants with regards to the walkway. Once initiated, the progression of gait was toward the same direction in all conditions. Foot placements, standardised according to the height of the participants (McIlroy and Maki, 1997), corresponding to the four starting angles were traced on the force platform and signs indicating the starting angles were posted at eye level approximately 6m from the starting position. At the start of each trial participants positioned themselves toward the instructed starting angle and looked straight ahead at the corresponding sign. Starting angles were presented randomly throughout two blocks of 32 trials during which participants walked at either a self-selected normal or fast speed. The order of the walking speed was alternated between participants. Each condition was repeated eight times for a total of 64 trials. At the start of the experiment, participants were allocated practise trials in order to become familiar with the protocol. There was a rest period between blocks of speed conditions as well as when requested by the participants.

Data Analysis

In order to measure the PA, the CoP (Fig. 1.5 and 1.6), calculated using GRF and moments, was analysed at the furthest posterior and lateral displacement of the CoP toward the Swing limb (event A), which occurred prior to Swing heel-off (MacKinnon, Bissig et al., 2007). CoP coordinates were taken with regards to the average position during the 250ms which preceded the start signal. CoM velocity (Fig. 1.3 and 1.4) was obtained by integrating the shear forces in the desired (Fy) and perpendicular (Fx) direction of gait over time (Shimba, 1984) with integration constants equal to zero (initial CoM velocity null) (Breniere, Do et al., 1987). The CoM velocity in both the desired and perpendicular directions were analysed at event A as well as just prior to Swing heel strike at which the participants stepped off the force platform (event B). This event was determined using the last peak in the vertical ground reaction force (Fig. 1.1 and 1.2) (Breniere and Bril, 1998).

Insert Figure 1 here

Statistical analysis

Dependant variables were submitted to a repeated measure factorial ANOVA with within factors of Angle and Speed. A post hoc test (Tukey) was performed on all significant results ($\alpha=0.05$).

Results

All subjects were able to complete the task. Before analysis, twelve trials (nine from one subject, three from others) were removed because the participant had initiated gait with their left limb (n=8), three trials were discarded due to a data collection problem and one trial was removed because gait was initiated from the wrong starting angle.

The CoP trajectory remained essentially the same for all starting angles (Fig. 2.1 and 2.2). In all conditions the characteristic CoP trajectory, initial posterior shift toward the Swing limb followed by a shift toward the Stance limb and finally forward, was observed. The amplitudes of these shifts, however, were significantly different at the different starting angle and speed conditions. The CoM velocity in both the desired and perpendicular directions was also affected.

Insert Figure 2 here

Postural Adjustment

The ANOVA revealed a significant Angle/Speed interaction ($p<0.001$) of the lateral PA component (CoP displacement toward the Swing limb at event A) (Fig. 3.1). Compared to the 0° conditions, lateral displacement of the CoP toward the swing limb increased at the -15° conditions and decreased at the 15 and 30° conditions ($Ps<0.001$). Compared to the normal gait speed conditions, when gait was initiated at the fast gait speed the lateral displacement of the CoP toward the swing limb increased at the -15 and 0° starting angles ($Ps<0.01$), remained unchanged at the 15° starting angle ($p=0.178$), and decreased at the 30° starting angle ($P<0.001$).

The ANOVA of the posterior PA component (CoP displacement at event A) (Fig. 3.2) revealed a significant effect of Angle and Speed ($Ps<0.001$), but no significant interaction ($P=0.873$). Compared to the 0° conditions, posterior displacement of the CoP decreased at the 15 and 30° conditions ($Ps<0.001$). Compared to the normal gait speed conditions, the posterior displacement of the CoP increased for all starting angles at the fast gait speed.

Insert Figure 3 here

CoM velocity

At event A the ANOVA of the CoM velocity in the desired direction of gait revealed a significant Angle/Speed interaction ($P<0.001$). Compared to the 0° starting angle, the CoM velocity for the 15 and 30° starting angles, at both normal and fast gait, was significantly slower ($Ps<0.05$) and for the -15° starting angle, at fast gait only, was significantly faster ($P<0.001$) (Fig. 4.1 and 4.2). The CoM velocity in the desired direction of gait at the fast gait conditions was significantly faster than at the normal gait conditions for all starting angles (Ps<0.01).

The ANOVA of the CoM velocity in the direction perpendicular to gait at event A revealed a significant Angle/Speed interaction (P<0.01). Compared to the 0° conditions, the perpendicular CoM velocity was slower for the 15° fast and 30° normal and fast gait conditions (Ps<0.05) (Fig. 4.3 and 4.4). The perpendicular CoM velocity for the 15° normal and -15° normal and fast gait conditions was not significantly different from the 0° conditions (P=0.132, P=0.713 and P=0.969, respectively). At the fast gait conditions, the perpendicular CoM velocity of only the -15° starting angle was significantly faster (P<0.05).

At event B differences in CoM velocity between conditions were diminished. The ANOVA of the CoM velocity in the desired direction of gait revealed significant effects of Angle and Speed (Ps<0.001), but no significant interaction (P=0.351). Compared to the 0° conditions, only the 30° conditions (slower) were significantly different (P<0.001) (Fig. 4.1 and 4.2). The CoM velocity in the desired direction of gait was significantly faster at the fast gait conditions.

The ANOVA of the perpendicular CoM velocity revealed a significant effect of Speed (P<0.001), but no significant Angle/Speed interaction nor effect of Angle (P=0.304 and P=0.080, respectively) (Fig. 4.3 and 4.4). The perpendicular CoM velocity was significantly faster at the fast gait conditions.

Insert Figure 4 here

Discussion

The aim of gait initiation is to commence the progression of the CoM toward the desired direction of gait while maintaining upright balance. When gait is initiated straight ahead, the lateral displacement of the CoM does not directly contribute to forward progression, but is required in order to maintain balance while lifting the Swing limb for the first step (Breniere, Do et al., 1987). When GI is combined with a change in direction, in addition to maintaining upright balance, the acceleration of the CoM provoked by the lateral component of the PA is toward the desired direction of gait during negative GI and away from the desired direction of gait during positive GI. The present study observed the interaction between maintaining balance while lifting the Swing limb and the progression of the CoM toward the desired direction.

The reduced amplitude of the PA (lateral and posterior), when gait was initiated toward the positive directions, resulted in a reduced velocity of the CoM in both the desired and perpendicular direction of gait at event A. This result corresponds to the observations of Lyon and Day (1997). In order to provoke a greater displacement of the CoM toward the direction of the Swing limb, the acceleration of the CoM toward the Stance limb was reduced at the start of GI. Thus when the Swing limb was lifted and the CoP shifted underneath the Stance limb, the CoM was redirected toward the desired direction of gait with a greater acceleration. The reduction of the PA amplitude was greater when the change in direction was increased from 15 to 30°.

As predicted, the opposite trend occurred when gait was initiated toward the negative direction; the lateral component of the PA was increased and the posterior component remained unchanged. At the end of the PA, the CoM velocity in both the desired and perpendicular direction of gait was equivalent to that when gait was initiated straight ahead at a normal speed. However, when fast gait was initiated, the CoM velocity in the desired direction of gait at the end of the PA was greater than during straight ahead GI. Contrary to straight ahead and positive GI, when gait was initiated toward the negative direction, the CoM moved toward the direction of the Stance limb throughout GI. When the Swing limb was lifted and the CoP shifted underneath the Stance limb, either the CoM was above or beyond the Stance limb and no acceleration toward the Swing limb was provoked or if the CoM was still medial of the Stance limb, the acceleration of the CoM toward the Swing limb was not great enough to stop the movement of the CoM toward the Stance limb.

It was hypothesised that the CoM velocity at the start of GI would vary depending on the desired direction of gait, but that by heel strike of the first step, all differences would be eliminated. Results of the perpendicular CoM velocity at the end of GI partly support this hypothesis. For all starting conditions, the CoM is successfully directed toward the desired direction of gait by the first step. However, the amplitude of CoM velocity at the end of GI was not the same for gait initiated toward all directions. Compared to straight ahead GI, the CoM velocity toward the desired direction of gait was significantly slower at the end of GI when gait was initiated toward the 30° direction. This reduced velocity could be due to the lateral component of the PA, e.g. the acceleration of the CoM toward the Stance limb at the start of GI could not be overcome in time for the CoM velocity to reach the same speed by heel-strike of the Swing limb as when gait was initiated straight ahead. Additional adjustments are therefore required in this condition in order to achieve steady state gait at the desired speed. It is possible that the effect of the first step provides these necessary adjustments. When gait is initiated onto a higher level, the CoM velocity is slower at the first step than in level walking (Gelat, Pellec et al., 2006). The lifting of the body causes an additional forward acceleration of the COM and, by the end of the first step, the CoM velocity is the same whether gait is initiated onto the same or a higher level (Gelat, Pellec et al., 2006). This could also be explained by a shorter transitional step in order to optimize balance while turning toward the desired direction. Because participants stepped off the force platform during the first step, it was impossible to determine the CoM velocity after the heel-strike of the Swing limb. When CoM velocity of gait initiated toward the 30° direction would be equal to that of gait initiated straight ahead remains to be determined.

In order to observe gait initiated toward both the positive and negative directions, participants were instructed to initiate gait with their right limb. When gait is initiated from a predetermined limb, there is an augmented risk that the Swing limb bears less weight than the Stance limb during quiet stance (Henriksson and Hirschfeld, 2005). However, this tendency is less present in young adults, and because the Swing limb was predetermined for all conditions, it is supposed that if limbs were loaded unevenly, it would have occurred equally in all conditions. Thus the differences observed in the PA across conditions are due to the desired speed and direction of gait rather than differences in the weight bearing of each limb.

In the current study, it was observed that both the posterior and lateral components of the PA were modulated with regards to the direction and speed of the initiated gait so that the desired direction of gait was achieved by the first step of the Swing limb. Ongoing studies are being conducted in order to understand the effects of normal and pathological aging on the ability to generate appropriate PA during GI combined with a change in direction. A better understanding of the control mechanisms involved in GI will help improve clinical interventions for populations with limited functional capacities, such as frail older adults.

Acknowledgements

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Captions

Figure 1: Vertical ground reaction force (panels 1 and 2), CoM velocity toward the desired and perpendicular directions of gait (panels 3 and 4) and anterior posterior (AP) and medial lateral (ML) CoP displacement with regards to the initial starting position (panels 5 and 6) for a typical trial of a single participant. Panels 1, 3 and 5 are of normal and 2, 4 and 6 are of fast gait speeds.

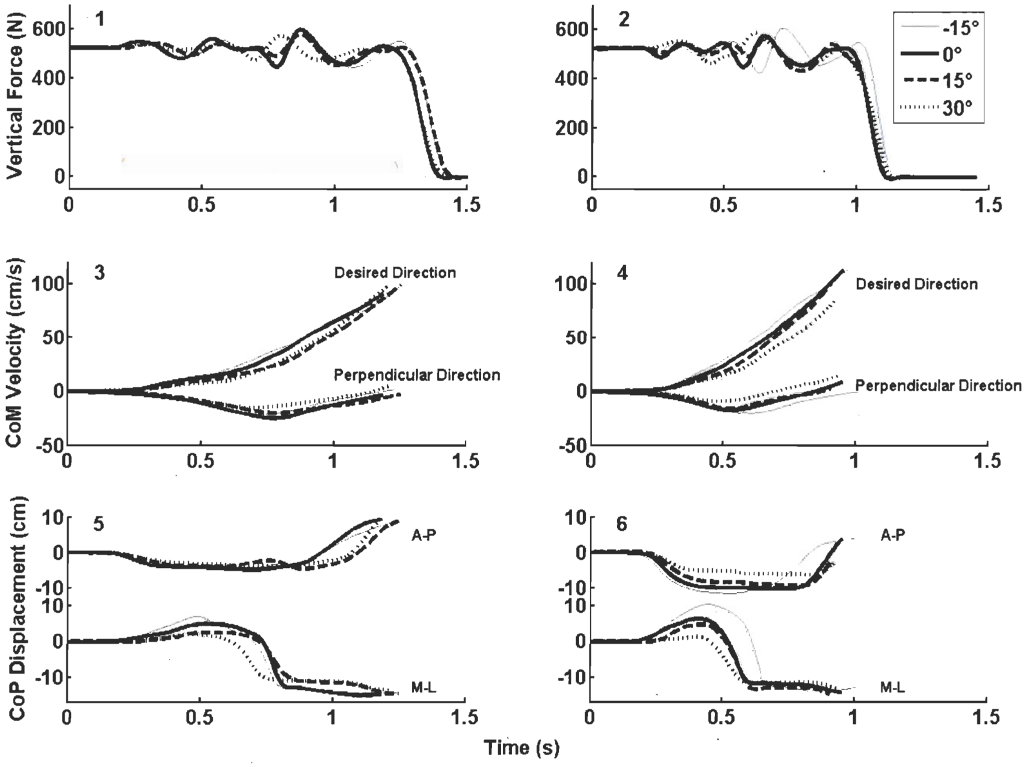
Figure 2: Typical CoP trajectories during normal (1) and fast (2) GI toward -15, 0, 15 and 30° directions. Event A (furthest posterior and lateral displacement of the CoP toward the Swing limb) is indicated by an X and Event B (Swing heel strike) by an O. The plot is of a typical trial of a single participant for each starting condition.

Figure 3: Lateral, toward the Swing limb (panel 1) and posterior (panel 2) displacement of the CoP between the start of GI and event A (furthest posterior and lateral displacement of the CoP toward the Swing limb). The lateral displacement has an Angle/Speed interaction ($P<0.001$); lateral displacement toward the Swing limb is increased from normal to fast conditions for the -15 and 0° directions but decreased at the 30° direction ($Ps<0.01$). The posterior displacement is increased from normal to fast GI for all directions ($P<0.001$)

Figure 4: Average values of CoM velocity at events A and B (furthest posterior and lateral displacement of the CoP toward the Swing limb and Swing heel strike) toward the desired (panels 1 and 2) and perpendicular (panels 3 and 4) directions of gait for the

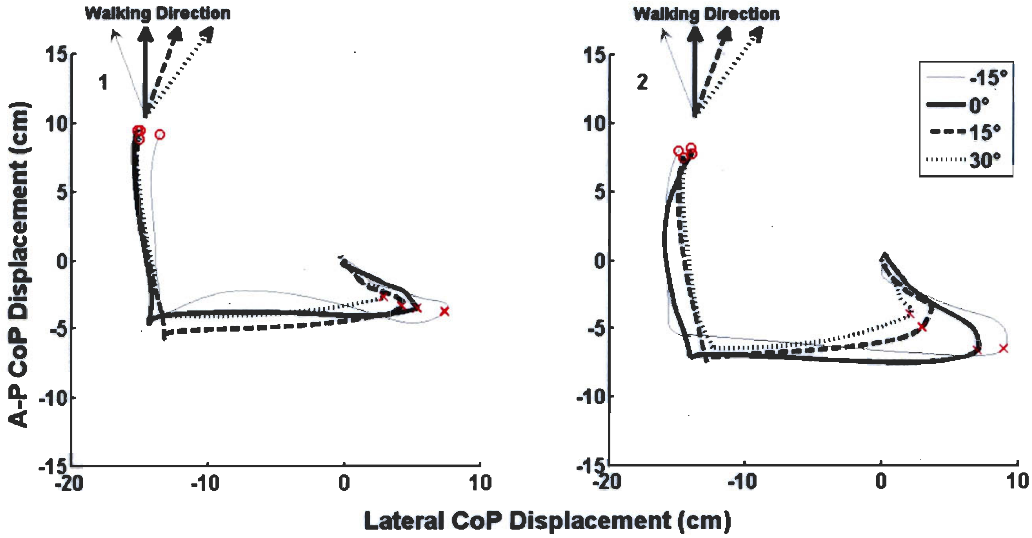
normal (panels 1 and 3) and fast (panels 2 and 4) gait speeds. The error bars represent 95% confidence interval. The horizontal bars indicate significant differences between GI combined with a change in direction and straight ahead GI ($P<0.05$).

Figure 1



1
2
3
4
5
6
Vertical Force (N)
600
400
200
0
-15°
0°
15°
30°
CoM Velocity (cm/s)
100
50
0
-50
Desired Direction
Perpendicular Direction
CoP Displacement (cm)
10
0
-10
A-P
M-L
0
0.5
1
1.5
Time (s)

Figure 2



Walking Direction
1
Walking Direction
2
-15°
0°
15°
30°
A-P CoP Displacement (cm)
15
10
5
0
-5
-10
-15
-20
-10
0
10
Lateral CoP Displacement (cm)

Figure 3

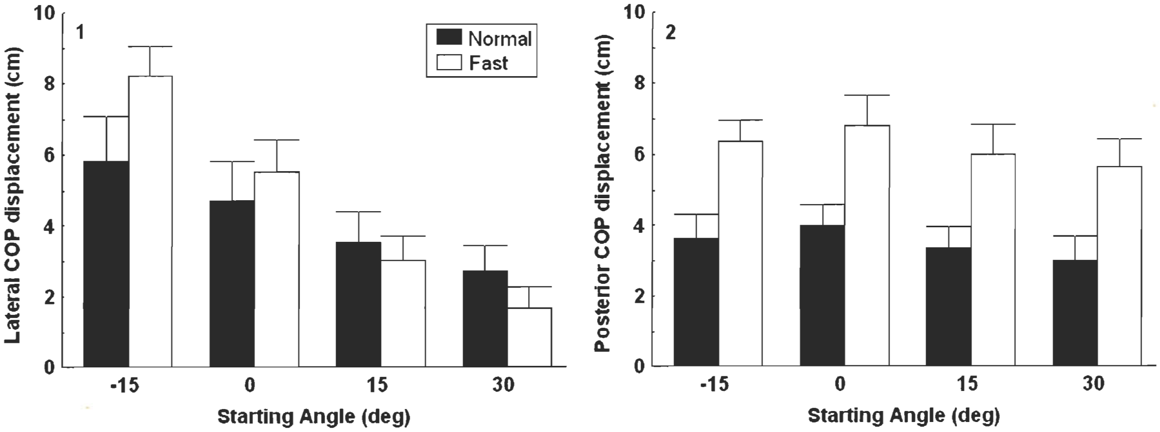
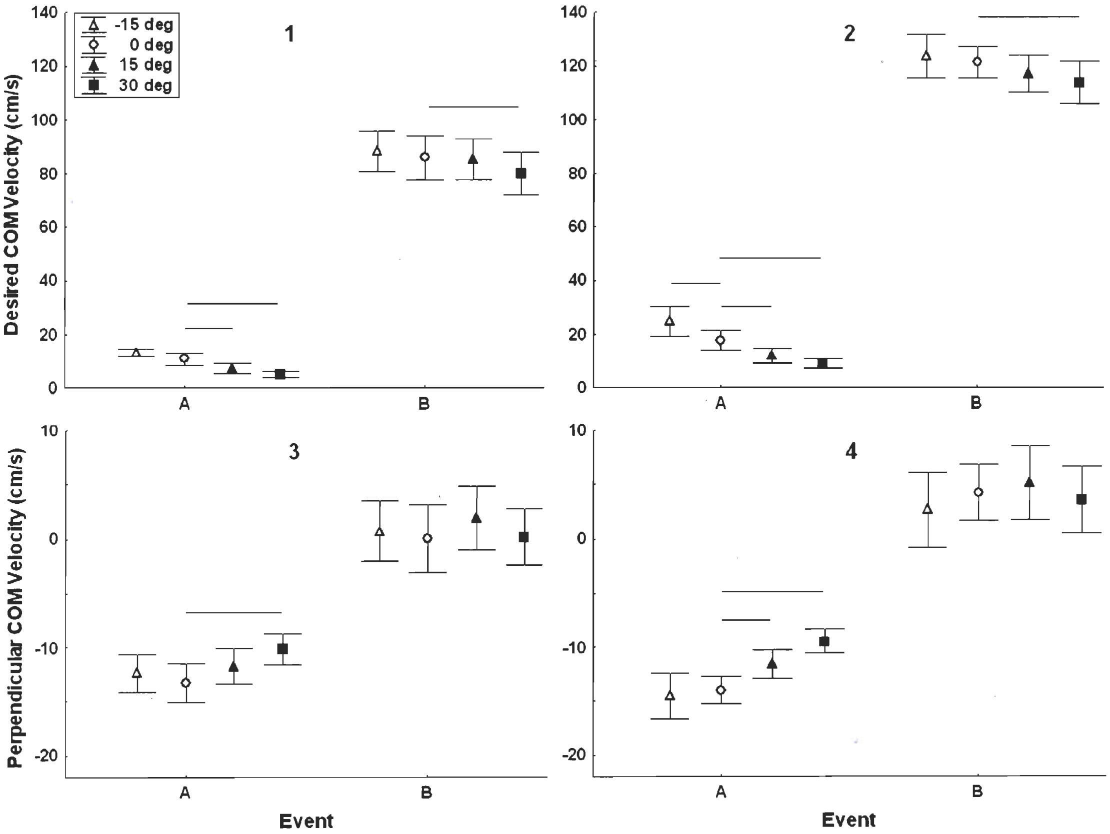

1
Lateral COP displacement (cm)
0
2
4
6
8
10
Normal
Fast
-15
0
15
30
Starting Angle (deg)
2
Posterior COP displacement (cm)
0
2
4
6
8
10
-15
0
15
30
Starting Angle (deg)

Figure 4



1
2
3
4
-15 deg
0 deg
15 deg
30 deg
Desired COM Velocity (cm/s)
Perpendicular COM Velocity (cm/s)
140
120
100
80
60
40
20
0
10
0
-10
-20
A
B
Event

Chapter IV – General Conclusion

Gait initiation, the transition from quiet stance to steady state gait is the result of stereotypic postural adjustments which can be modulated in function with the desired parameters of the intended gait. During straight ahead gait, it was shown that the posterior displacement of the CoP accounted for the majority of the forward momentum of the CoM [17]. It remains to be determined whether the modified CoP shift produced while gait is initiated with a change in direction is sufficient to produce the desired movement, or whether other actions such as change in trunk position, are required.

The extent to which GI can be modified once it has began, is a future area of interest. In order to study this phenomenon, a study which measures reaction times during the different phases of GI is underway. It is hypothesised that the attentional demands are increased during the phases of GI in which stability is decreased [31, 32]. This would be an indication that body has an increased capacity of fine tuning movement during these phases. This hypothesis could be further tested by observing whether it is possible to stop or modify (direction and speed) GI during its execution.

The long term goal of improving the fundamental understanding of GI is to develop better treatment and rehabilitation techniques which will aide populations with movement disorders.

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